



# **Preliminary results from global and Regional ensemble ocean forecasting**

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| Report Documentation Page                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                     |                                                           | Form Approved<br>OMB No. 0704-0188                  |                                 |
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**Objective:** Extend forecasting from:

- Deterministic (single forecast) to stochastic (probabilistic) *in*
- Space (from regional to global) *and*
- Time (from ~7 days to ~30-60 days)
- Via ensemble modeling



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**Outline:**

- Initial capability based on NCOM in Gulf of Mexico
- Preliminary Global “ensembles of opportunity”
- Proposed global ensemble forecasting
- Based on HYCOM
- Unique and specific challenges



# RELO NCOM/NCODA

*NCODA* - NRL Coupled Ocean Data Assimilation - Cummings, QJRMS, 2005

*NCOM* - Navy Coastal Ocean Model – Barron, et al., Ocean Modeling, 2006

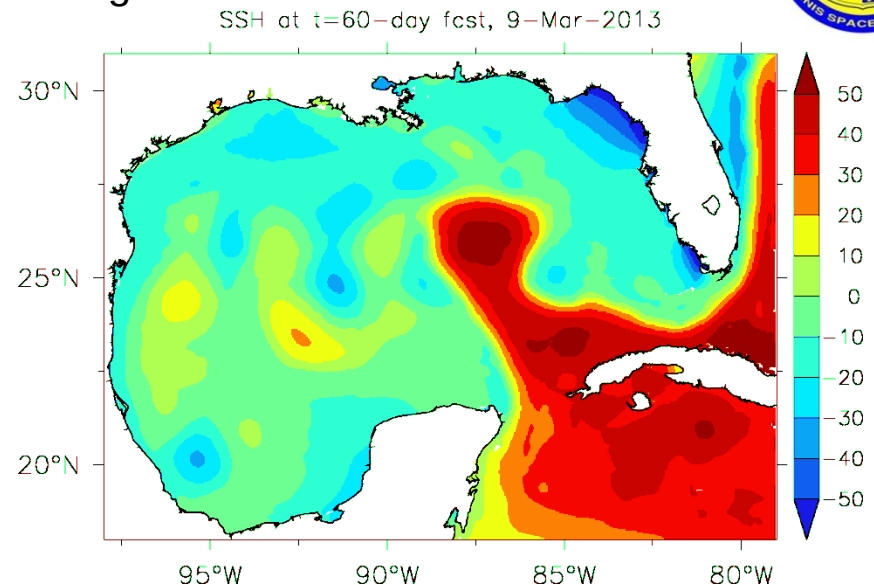
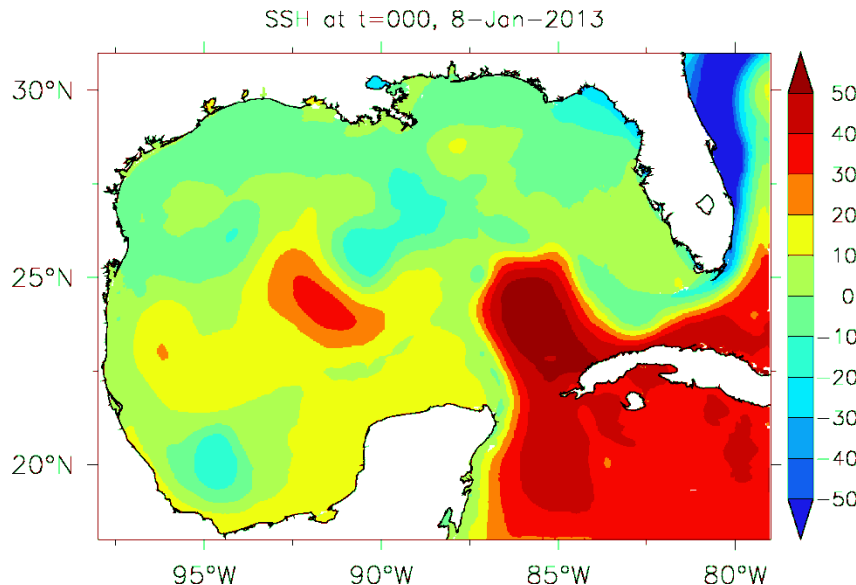
*COAMPS* - Coastal Ocean Atmosphere Mesoscale Prediction System

- **3km grid / 49 levels (33 sigma, 16 z)**
- **NRL DBDB2' bathymetry**
- **COAMPS 27km forcing**
- **Lateral BCs by G-HYCOM (GOFS 3.0)**
- **OSU OTIS tides at boundaries**
- **Assimilates data from any source available in real-time**
  - **Satellites (SST, SSH)**
  - ***In situ* obs (XBTs, CTDs, floats, buoys gliders, ships)**
- **3D Forecasts to 72 hours/60 days**
  - **T, S, currents, elevation**

# Task 1: Running two “control runs”



## Sea Surface Height

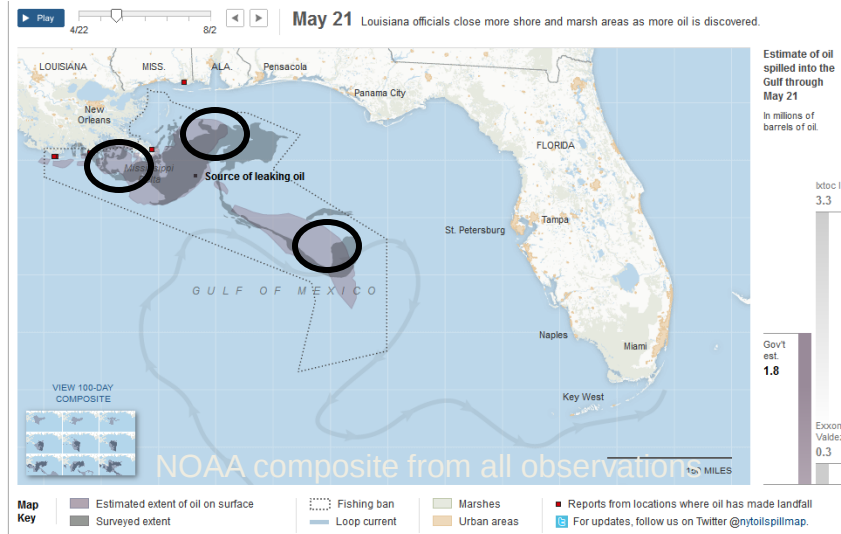


- Control run no. 1: Produces a 3 day forecast once per day  
(assimilate local profile observations only, 24 hr window)
- Control run no. 2: Produces a 60 day forecast once per week  
(assimilate synthetic and observed profiles, 7 day window)

**Note:** 60 day forecasts required the construction “high-frequency” climatological forcing files (more realistic spatial and temporal variability than persistence or seasonal/annual climatology)

*e.g. 2003-2012; 10 records for Jan 1 000z, 003z, 006z... - Dec. 31 021z*

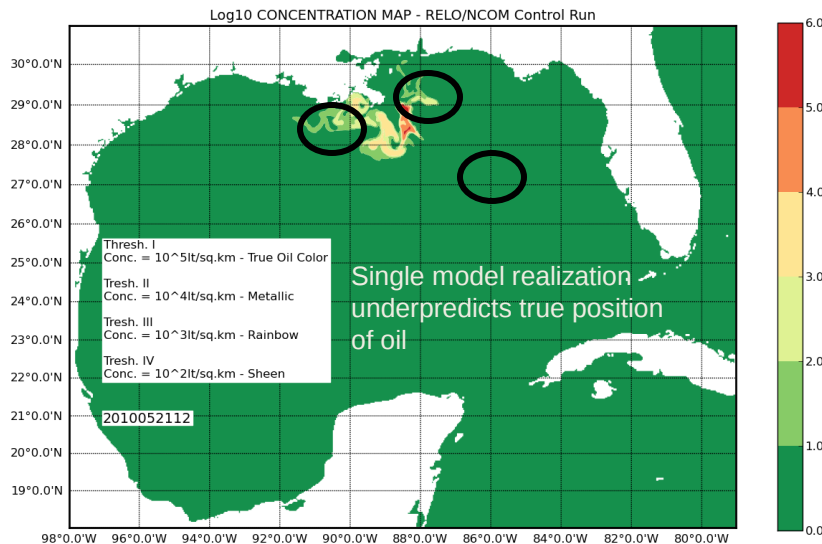
## Oil Map integrating NOAA calibrated estimates and actual observations



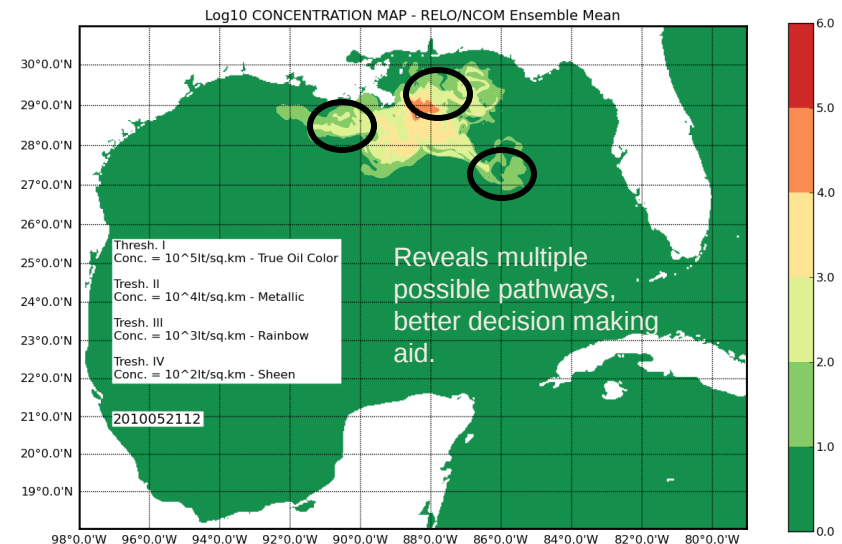
## Why Ensembles?

- Deterministic forecast only captures one possible trajectory and will likely diverge from reality esp. for extended range forecasts
- Done properly, ensemble will include the true state
- Ensemble provides the forecast error/uncertainty
- Ensembles can be calibrated to refine the forecast

### May 21, 2010 Control Run



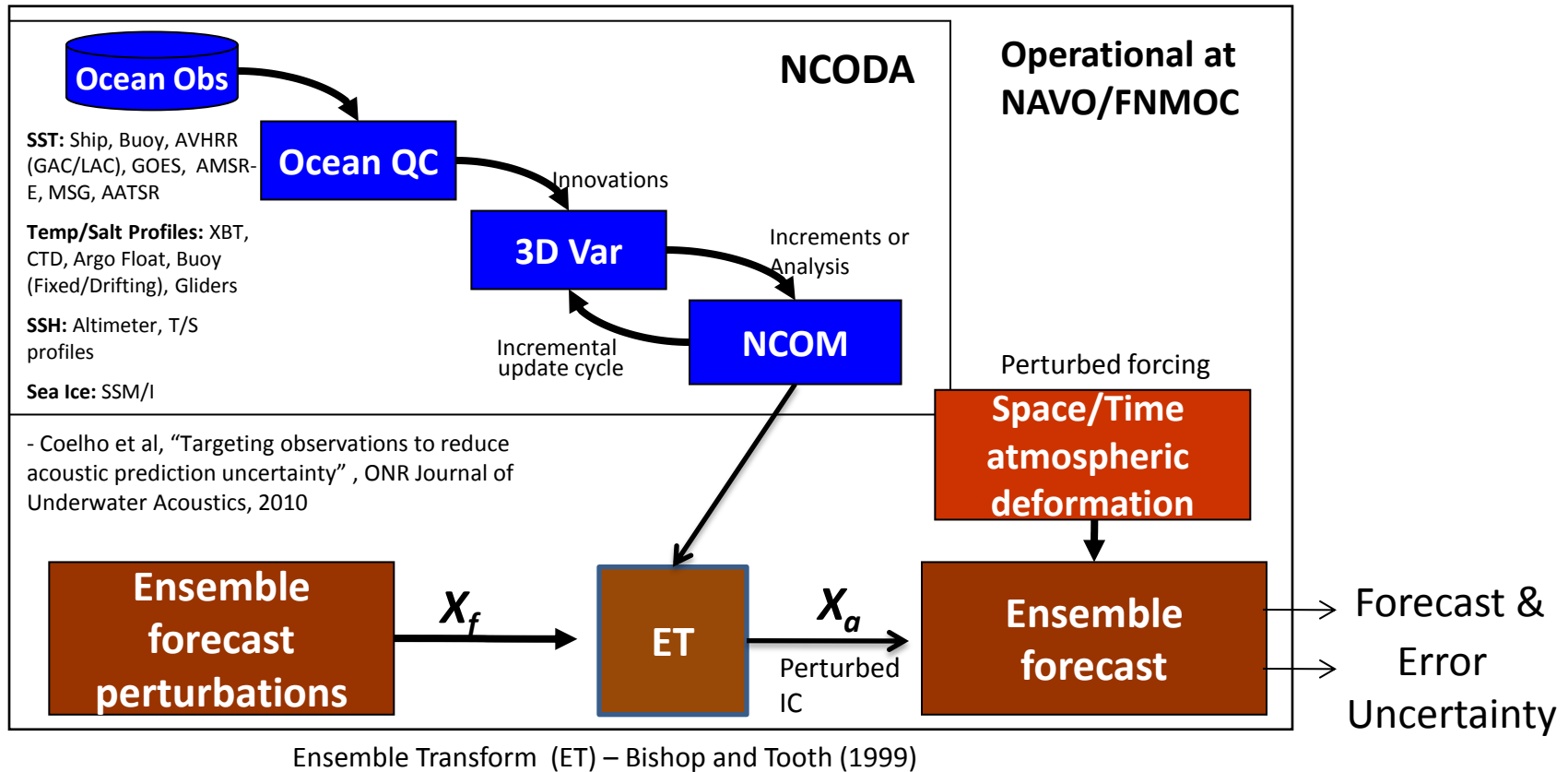
### May 21, 2010 Ensemble Mean



Color bar is concentration and is correlated to thresholds from BONN agreement for oil appearance code



# Ensemble Approach to Quantifying Ocean Uncertainty



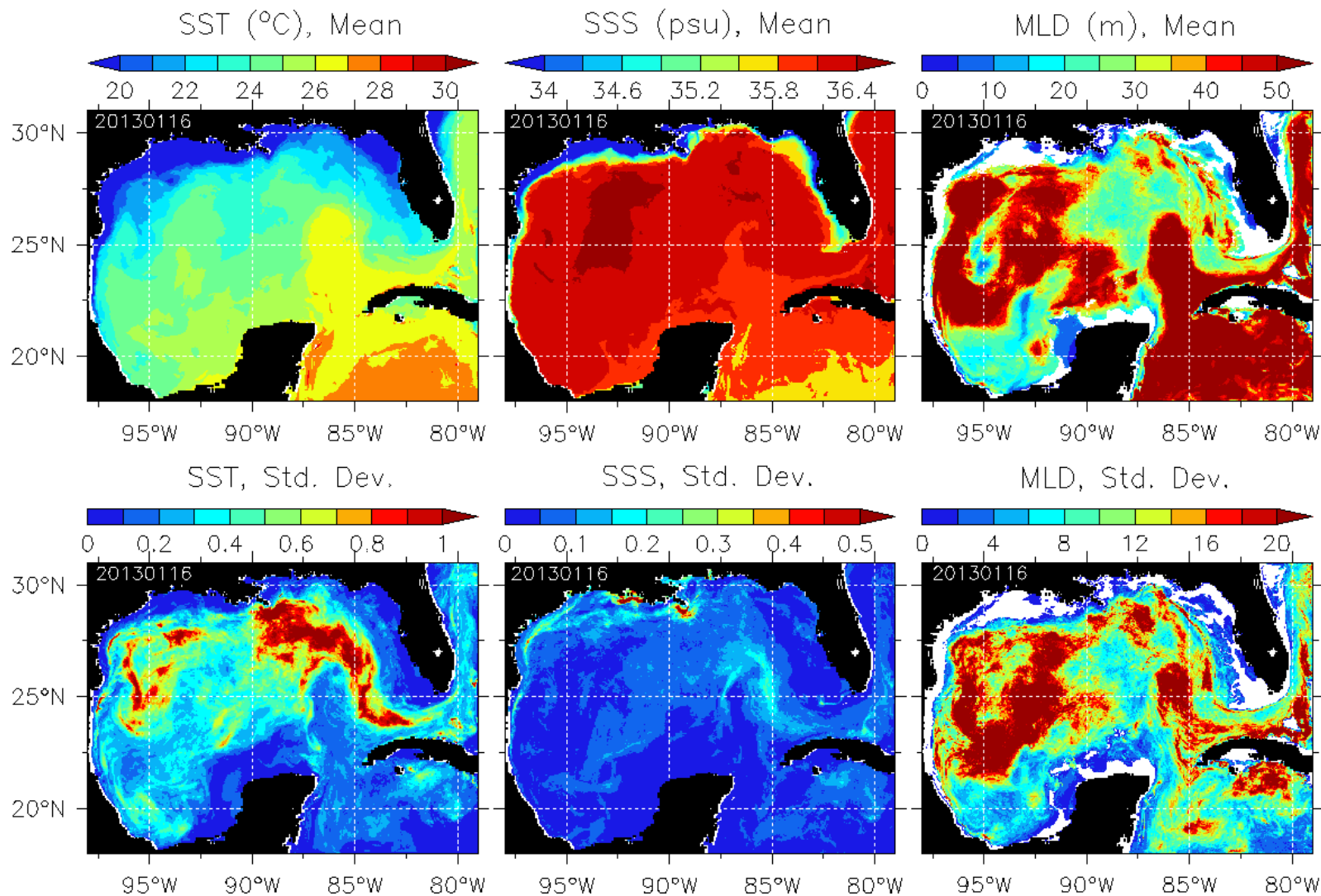
The spread and growth of the Initial Condition (the perturbations) is determined by the forecast error variance via the Ensemble Transform

Analysis error estimate – standard dev. of the ensemble set

Uncertainty – described through the PD of state parameters through the ensemble

# Ensemble Fields for 16 Jan. 2013 (the analysis)

Calculated over 20 ensemble members





# Ensemble Forecasting Concept of Operations (CONOPS)

24 hour forecasts are run daily,  
8-week forecasts are run every weekly (Sunday)

## *To Date:*

Jan. 27 – Mar. 24

Feb. 03 – Mar. 31

Feb. 10 – Apr. 07

Feb. 17 – Apr. 14

Feb. 24 – April 21

Mar. 03 – Apr. 28

Mar. 10 – May 05

Mar. 17 – May 12

Mar. 24 – May 19

Mar. 31 – May 26

Apr. 07 – Jun. 02

Apr. 14 – Jun. 09

Apr. 21 – Jun. 16

Apr. 28 – Jun. 23

May 05 – June 30

..... - .....

- *Currently running on NRL Linux Cluster*
- *32 ensemble members*
- *Daily run: 96 CPUs, ~ 2 hours*
- *Weekly run: 120 CPUs for 5 members, ~3.5 hours  
(32 members takes ~21 hours)*
- *Each member ~4.2 GB in netCDF format  
(~135 GB for 60-day 32 member ensemble once per day)*
- *Will eventually run at Naval Oceanographic Office  
(but stringent transition process and CONOPS)*

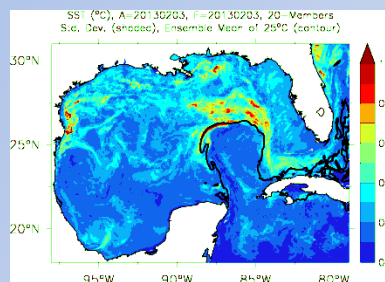
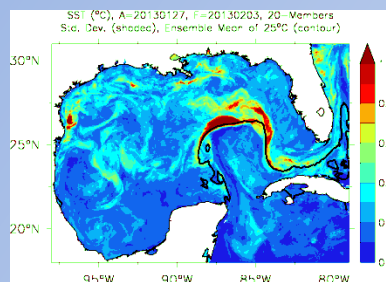
## Forecast

## Analysis

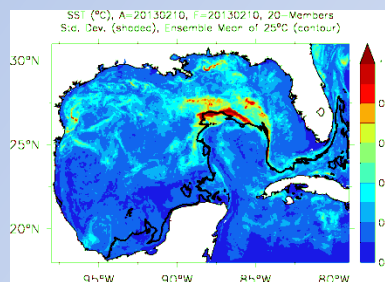
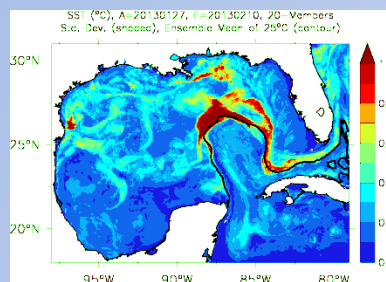
## Forecast

## Analysis

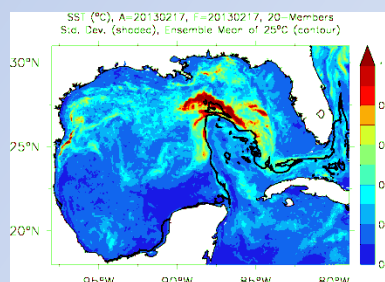
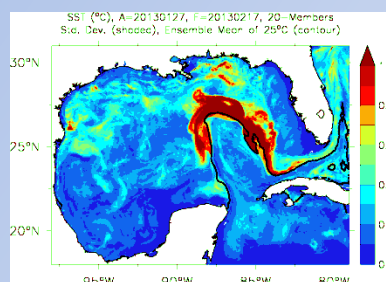
Feb. 03  
1 wk.



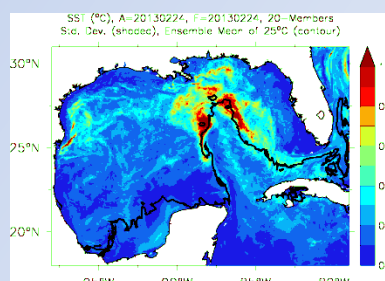
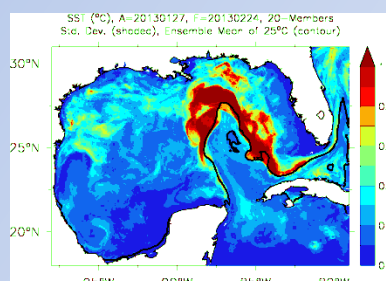
Feb. 10  
2 wk.



Feb. 17  
3 wk.

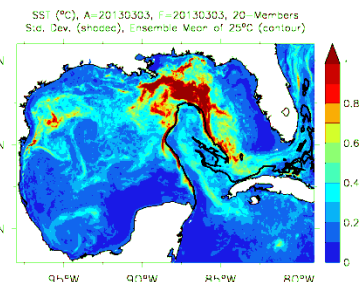
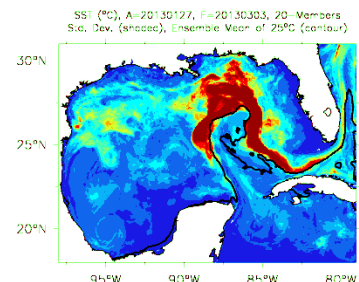


Feb. 24  
4 wk.

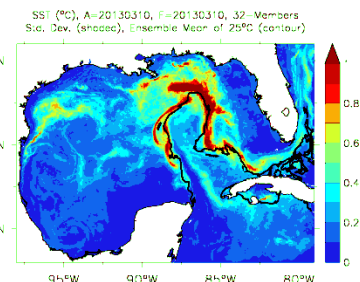
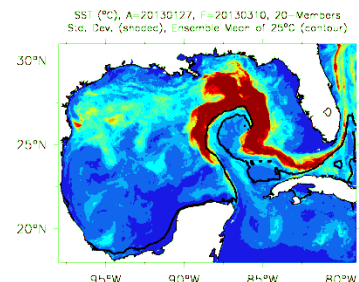


Corresponding Analysis

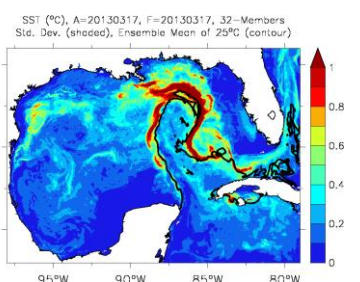
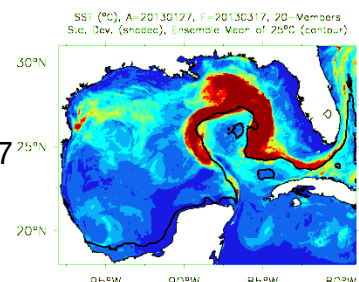
Mar. 03  
5 wk.



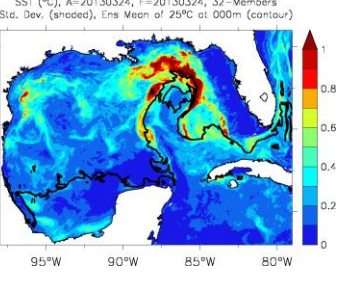
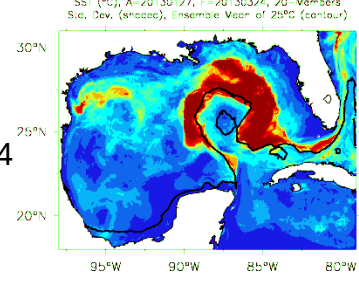
Mar. 10  
6 wk.



Mar. 17  
7 wk.

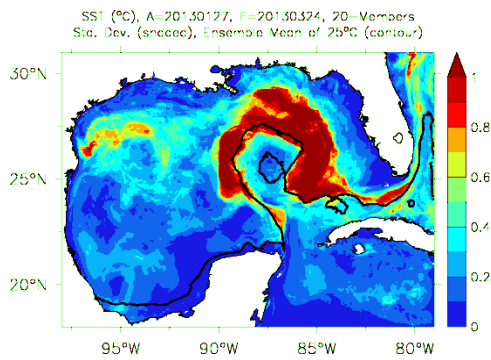


Mar. 24  
8 wk.

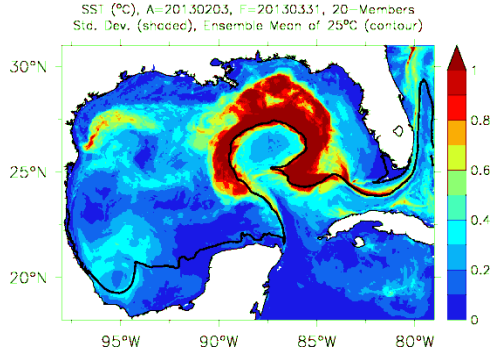


# 8 week forecasts

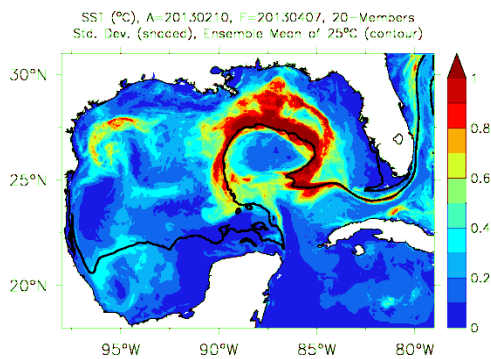
Jan. 27  
Analysis  
Mar. 24  
Forecast  
8 wk.



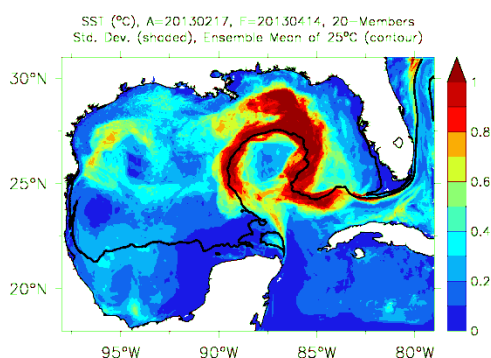
Feb. 03  
Analysis  
Mar. 31  
Forecast  
8 wk.



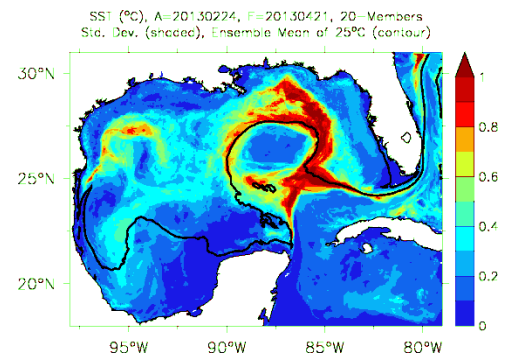
Feb. 10  
Analysis  
Apr. 07  
Forecast  
8 wk.



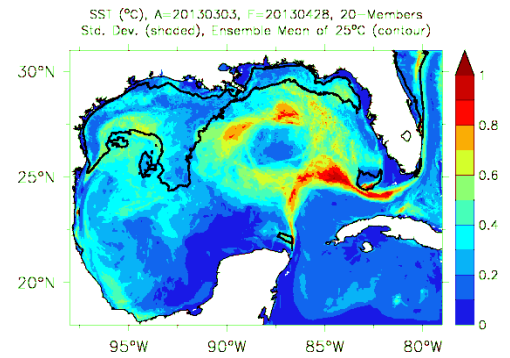
Feb. 17  
Analysis  
Apr. 14  
Forecast  
8 wk.



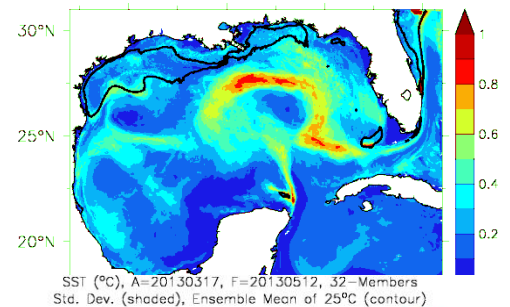
Feb. 24  
Analysis  
Apr. 21  
Forecast  
8 wk.



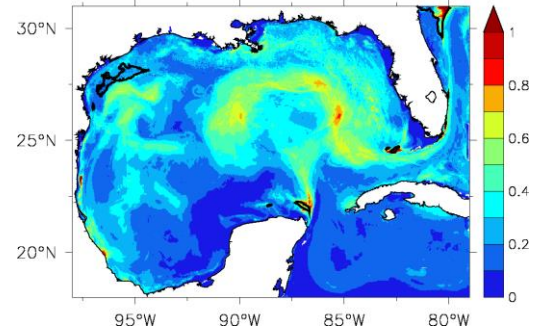
Mar. 03  
Analysis  
Apr. 28  
Forecast  
8 wk.



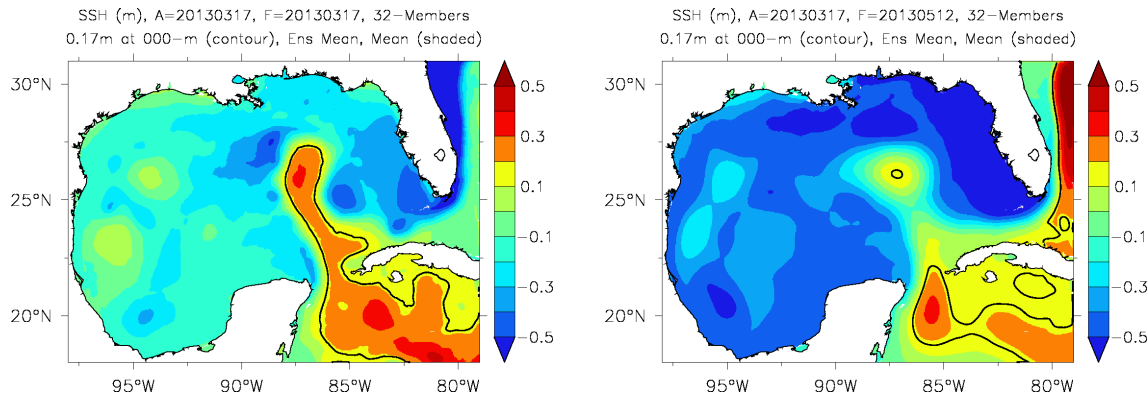
Mar. 10  
Analysis  
May 05  
Forecast  
8 wk.



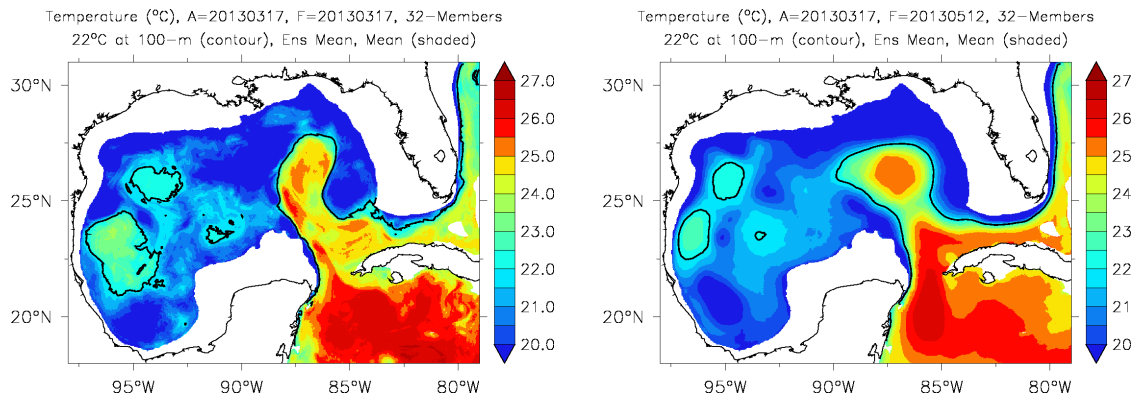
Mar. 17  
Analysis  
May 12  
Forecast  
8 wk.



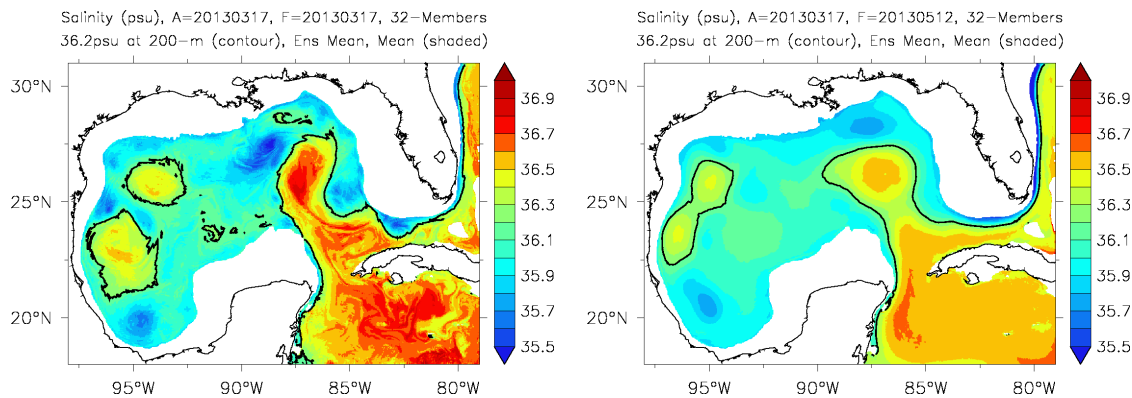
# GoM Ensemble Modeling March 17 Analysis and 60-day forecast (12 May 2013)



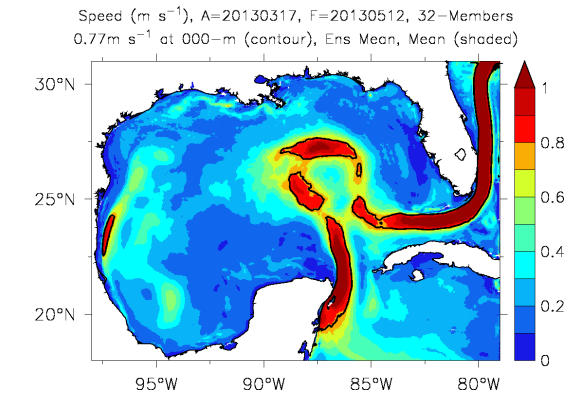
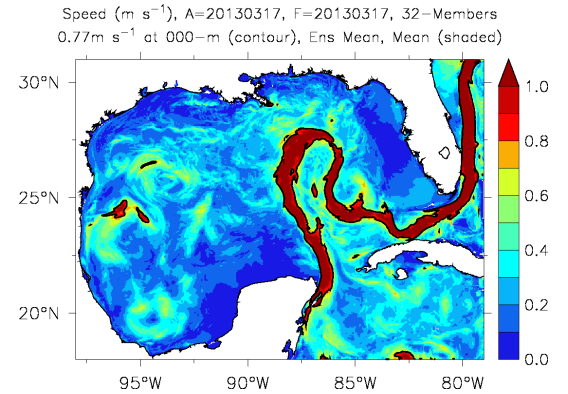
**Ensemble mean 17 cm SSH**



**Ensemble mean temp (22C @ 100m)**



**Ensemble mean salt (36.2 @ 200m)**



**Ensemble mean Speed  
(1.5 kt isotach)**



# Risk Assessment for Planning and Operations

**Weighs the likelihood of occurrence (probability)  
with the severity of risk (impact threshold)**

| Risk Management Matrix<br><b>OPNAVINST 3500.39B</b> |                                 | P R O B A B I L I T Y |           |            |          |              |
|-----------------------------------------------------|---------------------------------|-----------------------|-----------|------------|----------|--------------|
|                                                     |                                 | <b>A</b>              | <b>B</b>  | <b>C</b>   | <b>D</b> |              |
|                                                     |                                 | Likely                | Probable  | May        | Unlikely |              |
| S E V E R I T Y                                     | <b>I</b> Death, Loss of Asset   | <b>1</b>              | <b>1</b>  | <b>2</b>   | <b>3</b> |              |
|                                                     | <b>II</b> Severe Injury, Damage | <b>1</b>              | <b>2</b>  | <b>3</b>   | <b>4</b> |              |
|                                                     | <b>III</b> Minor Injury, Damage | <b>2</b>              | <b>3</b>  | <b>4</b>   | <b>5</b> |              |
|                                                     | <b>IV</b> Minimal Threat        | <b>3</b>              | <b>4</b>  | <b>5</b>   | <b>5</b> |              |
|                                                     |                                 | 1-Critical            | 2-Serious | 3-Moderate | 4-Minor  | 5-Negligible |

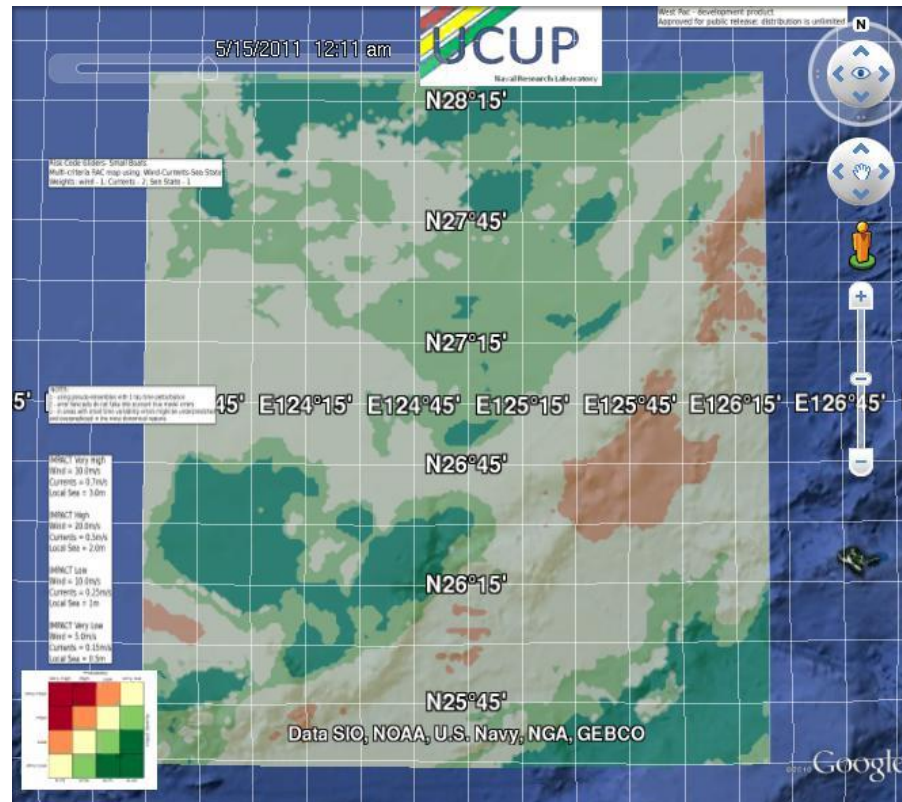
**Objective:** Identify areas and periods in the GOM over a 60 day long forecast where environmental conditions might produce operational impacts

- **Operations Safety/Warning System**

Variables: surface currents, vertical shear, wind, sea-state, SST, etc.

Thresholds: magnitude levels that will impose risk on operations, relative weighting and identification of individual critical levels (small boats, drill stems, etc.)

# Operational Safety/Warning System



## Impacts/Thresholds Examples

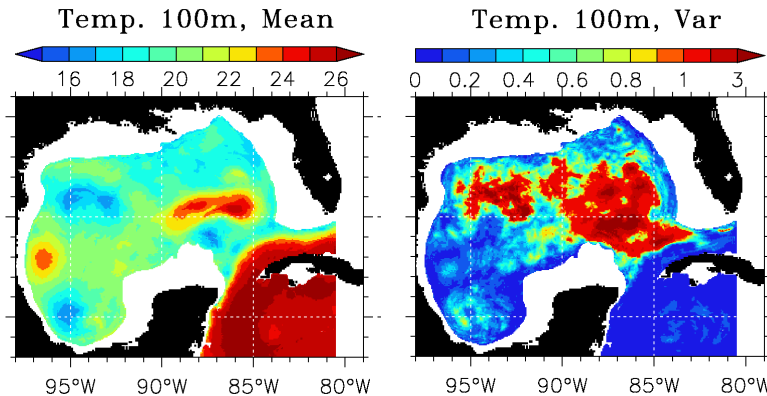
- **Surface Ocean Currents:**  
very high impact if above 0.7m/s; high impact if above 0.5m/s and below 0.7m/s; moderate impact if between 0.25 and 0.5m/s; low impact if above 0.15m/s.
- **Surface Winds :**  
very high impact if above 30m/s; high impact if above 20m/s; moderate impact if above 10m/s; low impact if above 5m/s;
- **Sea State:**  
very high impact if above 3m; high impact if above 2m ; moderate impact if above 1m; low impact if above 0.5m.

# Ensemble Approach to Ocean Forecasting



## Single-Model Approach:

Use one forecast system and perturb some aspect of that system (initial state and atmospheric forcing) then integrate forward to obtain a forecast.



$N$  different ensemble realizations

Note: Ensembles take  $N$  members as much computer time

Pro: develop one model

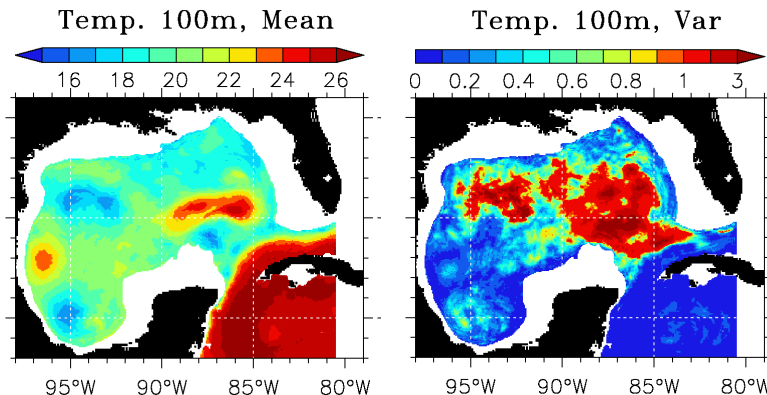
Con: do perturbations represent realistic variance?

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$N$  different ensemble realizations

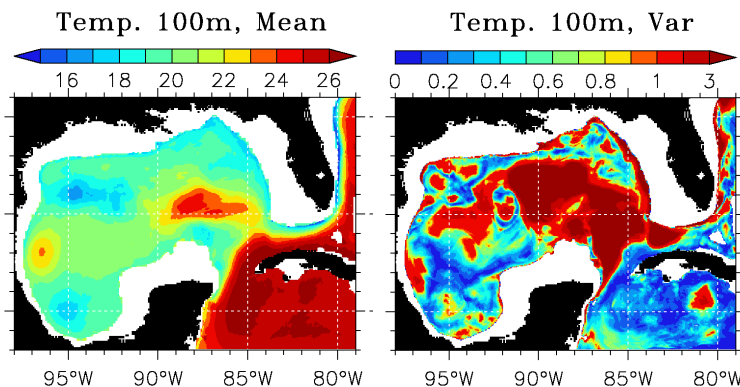
Note: Ensembles take  $N$  members as much computer time

Pro: develop one model

Con: do perturbations represent realistic variance?

## Multi-Model Approach:

Use forecast systems with different designs (physics, resolution, forcing, etc.), typically run by different operational centers or labs



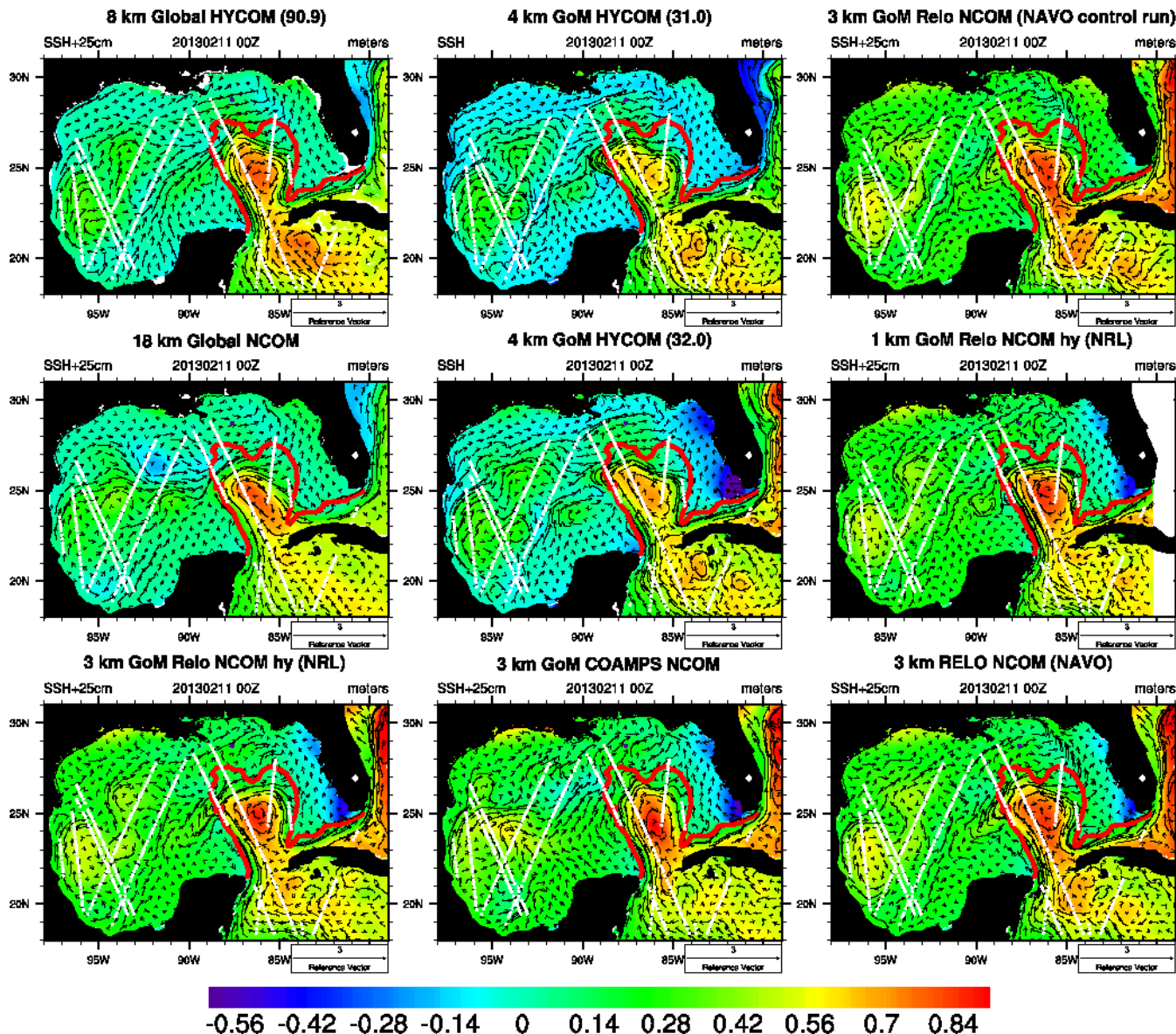
$N$  different forecast systems

Pro: more variety across members

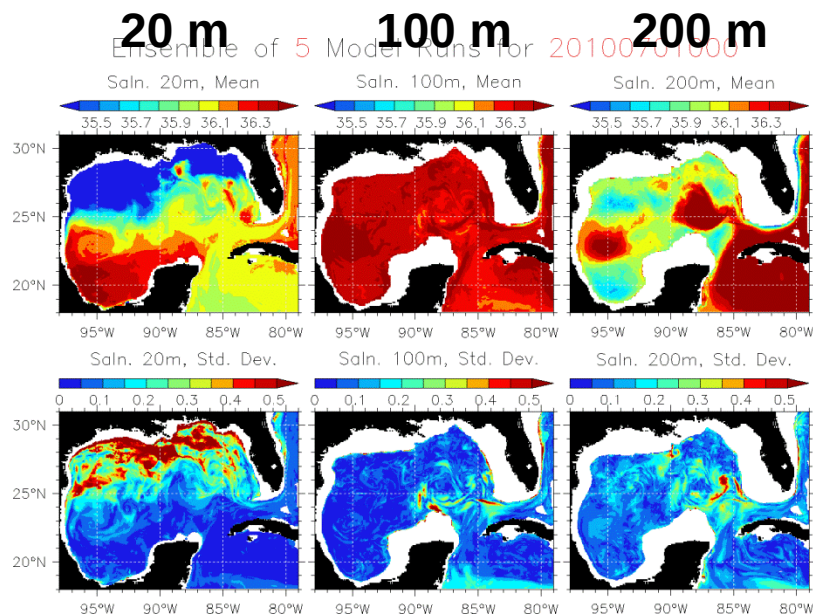
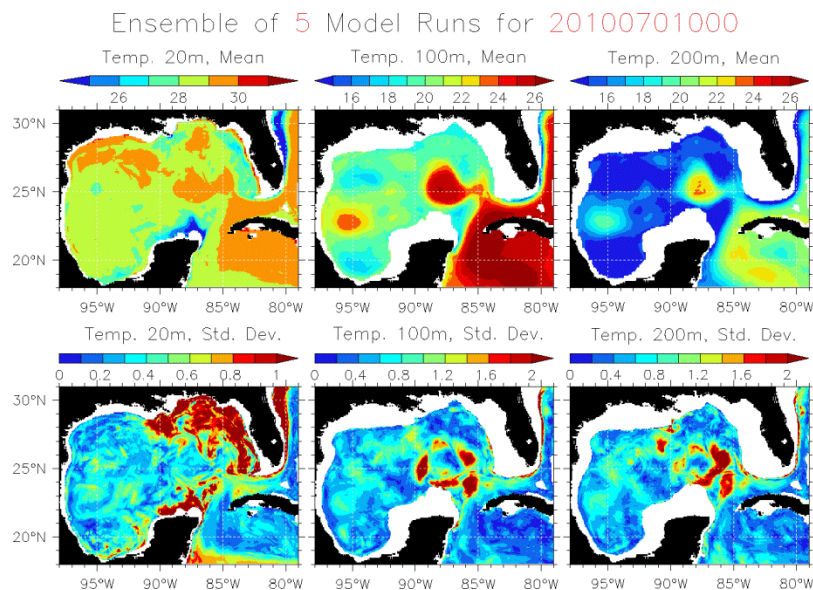
Con: limited number of members

# Multi-Model Comparison: Sea Surface Height

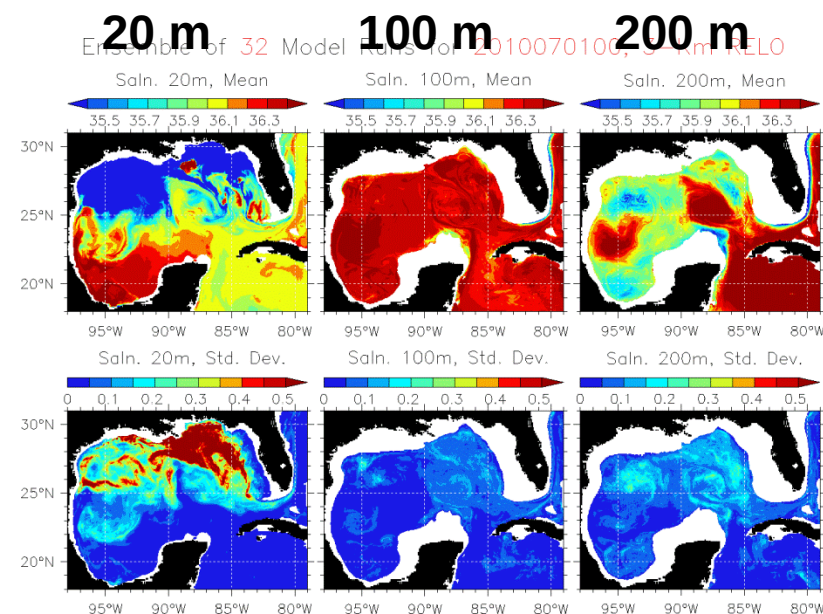
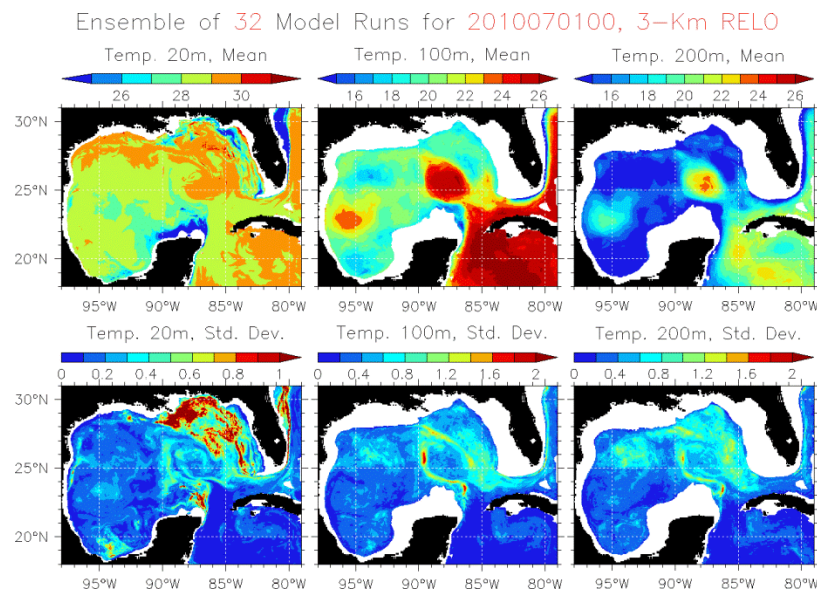
## 11 February 2013



## Multi-model Ensemble



## 32-member Single Model Ensemble



Temperature

Salinity

# Global “Ensembles of Opportunity”

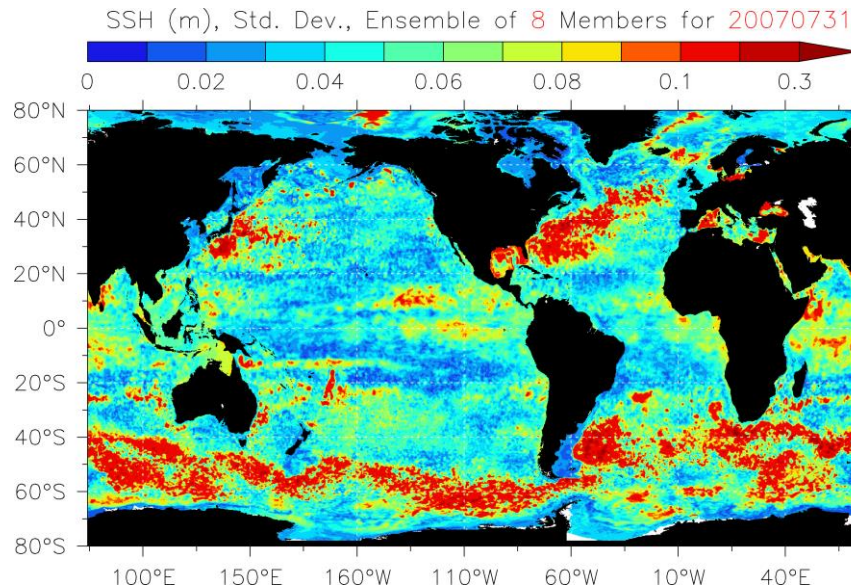


- There were several global experiments with ~3 month overlap that were run as part of the normal development and improvement process such that the global simulations that differ by some parameter setting or technique.
- **Not the proper way to develop and configure an extended range forecast capability (more on that soon).**

Set 1 (2007): 5 used Cooper-Haines, 3 used MODAS synthetics. Two used 35 layers instead of 27. Some used an updated version of NCODA and one used mixed layer depth to modify the MODAS synthetic, etc.)

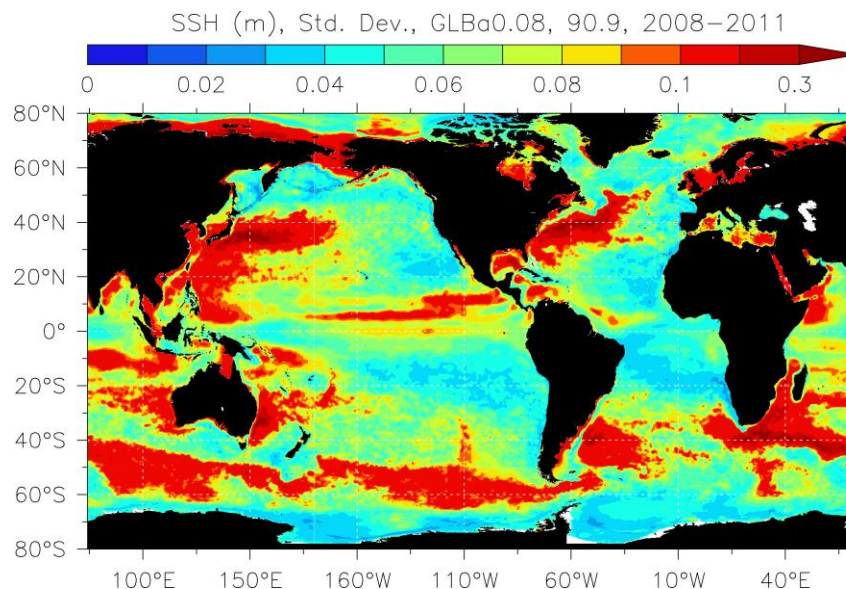
Set 2 (2012): All 3DVar, 32 vs. 41 layers, different ocean analysis configurations

# SSH: Global Ensemble Variance vs. Time Variance



SSH variance calculated over 8 different models on 31 July 2007.

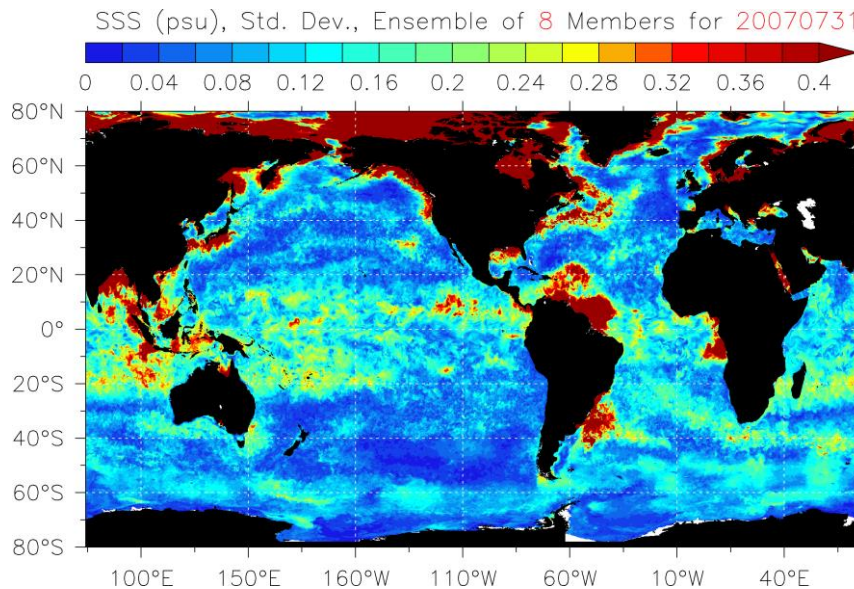
*Uncertainty due to errors*



SSH variance calculated from one simulation over 2008-2011.

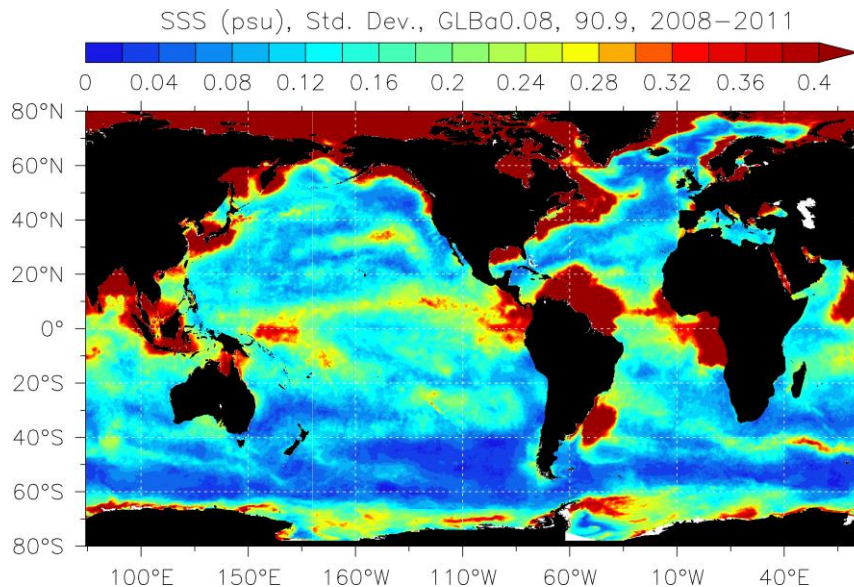
*Intrinsic uncertainty*

# SSS: Global Ensemble Variance vs. Time Variance



SSS variance calculated over 8 different models on 31 July 2007.

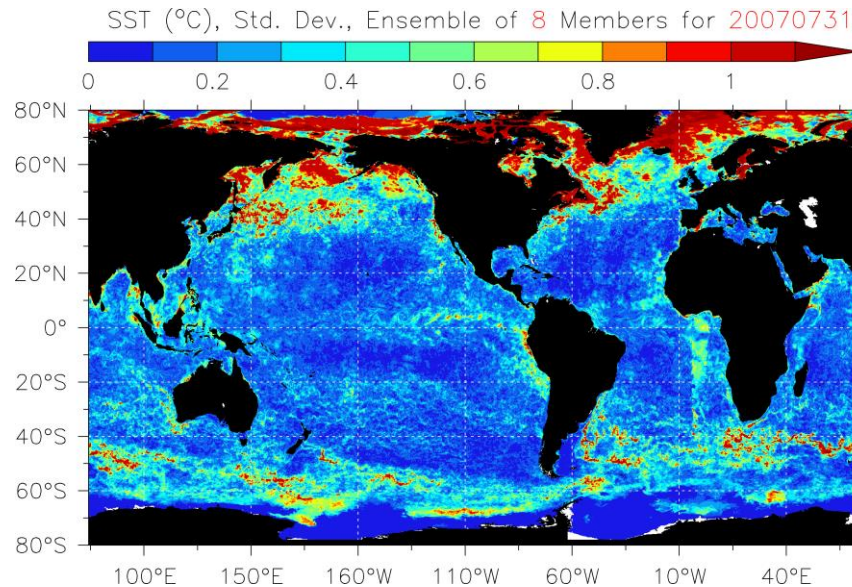
*Uncertainty due to errors*



SSS variance calculated from one simulation over 2008-2011.

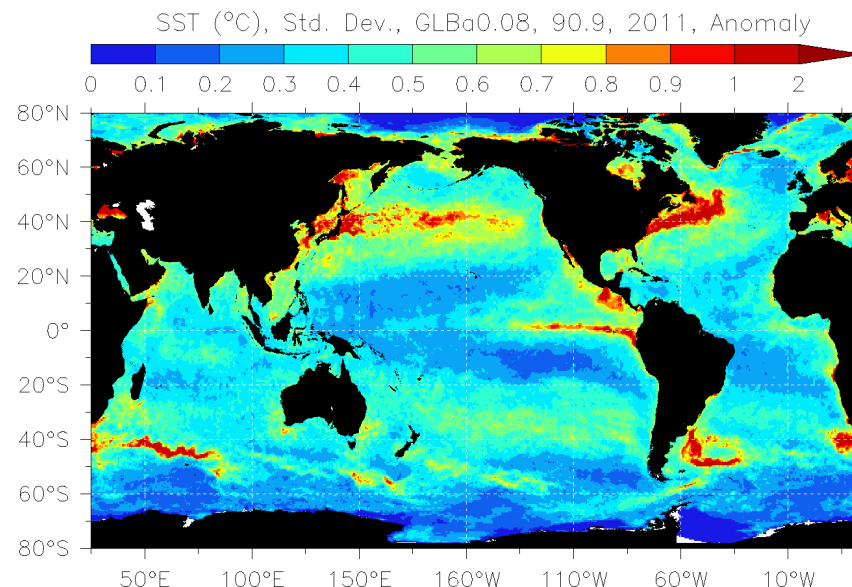
*Intrinsic uncertainty*

# SST: Global Ensemble Variance vs. Time Variance



SST variance calculated over 8 different models on 31 July 2007.

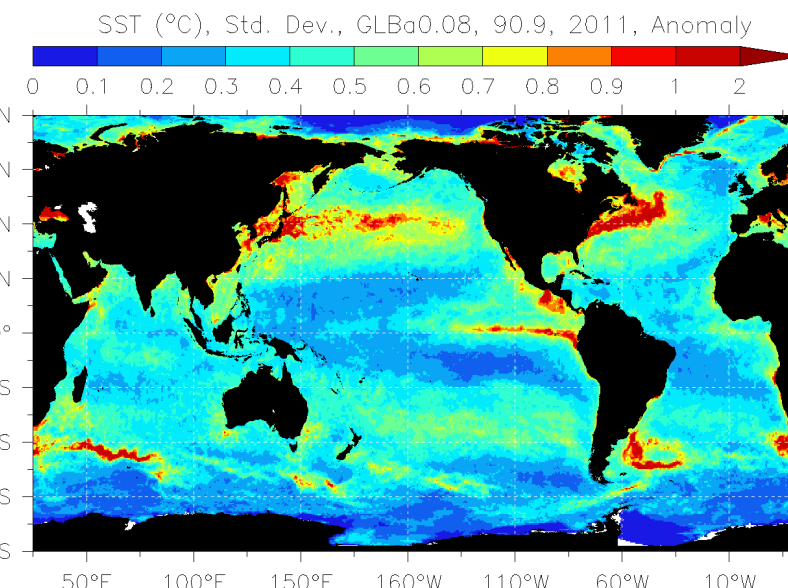
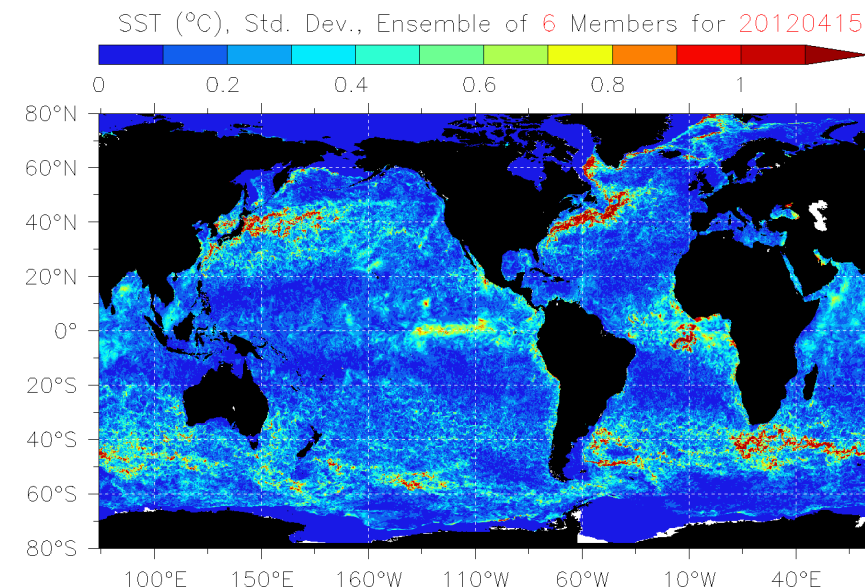
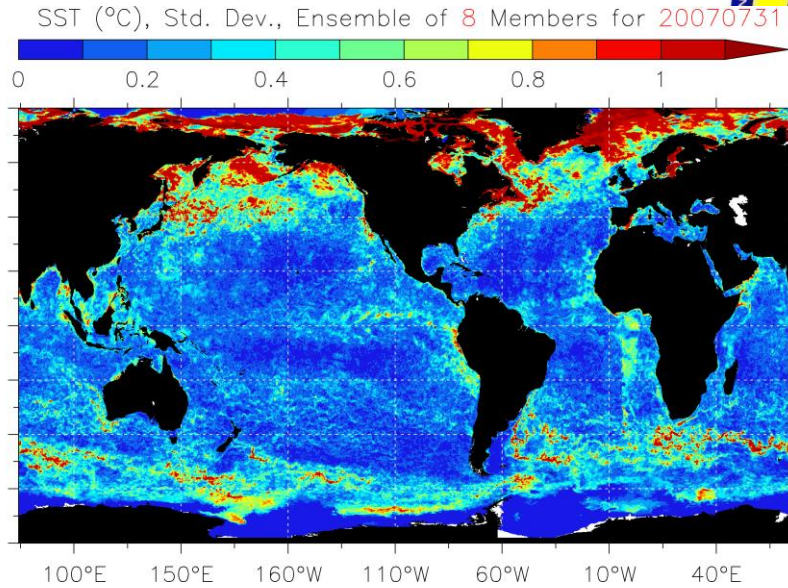
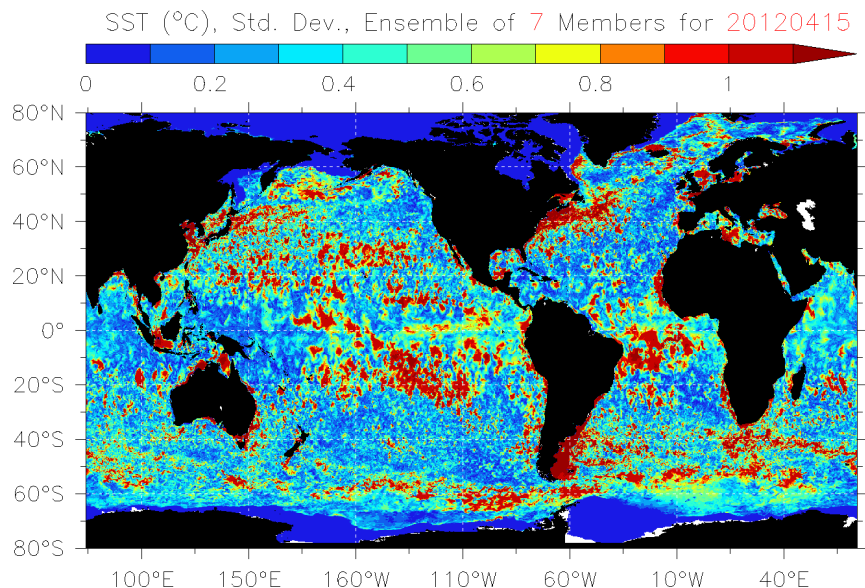
*Uncertainty due to errors*



SST variance calculated from one simulation over 2008-2011.

*Amplitude of the annual cycle removed*

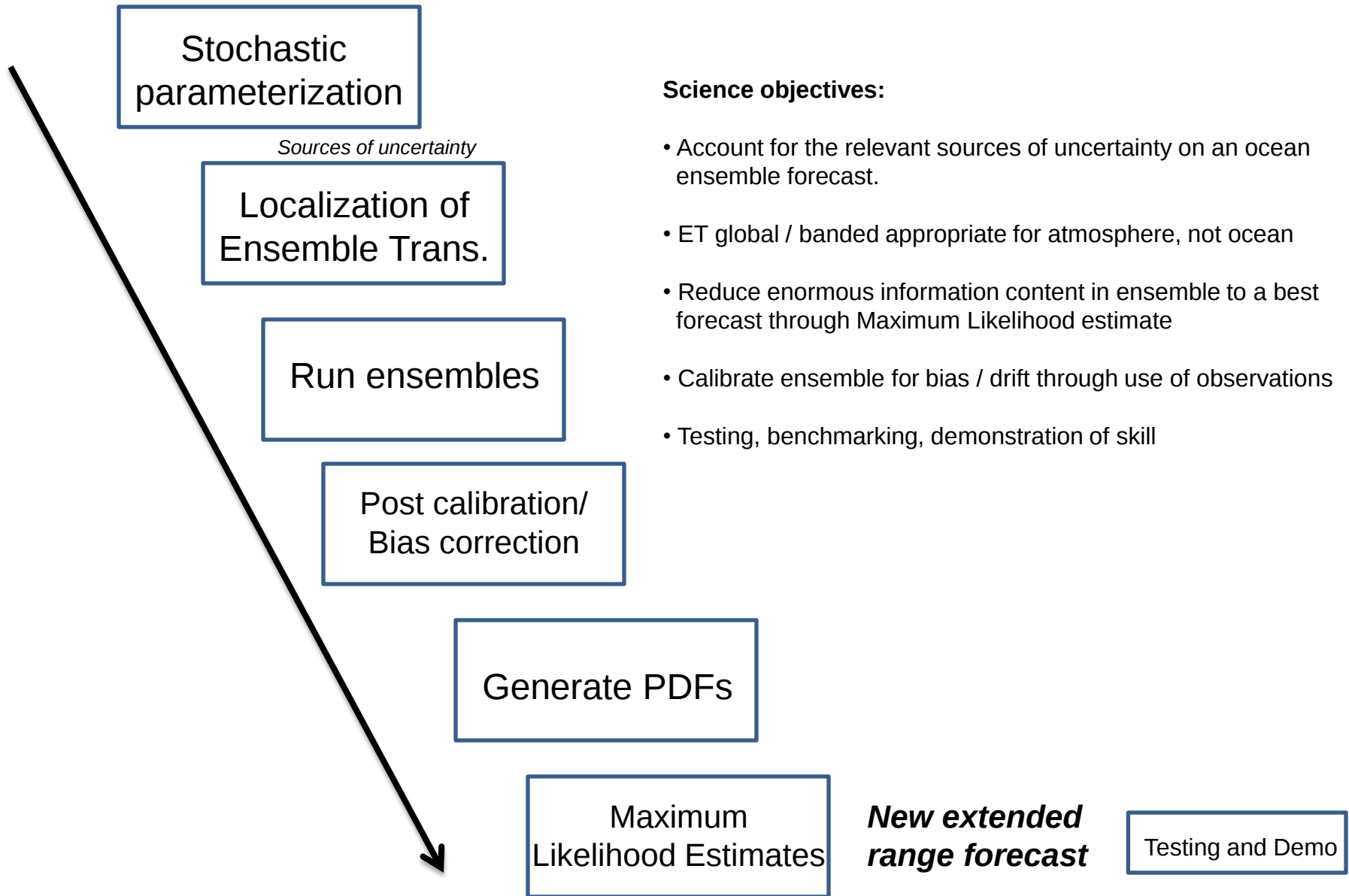
# SST: Global Ensemble Variance vs. Time Variance



**Experiment 25.0 excluded**

**from one simulation  
over 2008-2011.**

# Objective: Extend the Range of Ocean Forecasts in Space (up to global) and in time (up to 30 days) using a stochastic forecast capability



# Objective: Extend the Range of Ocean Forecasts in Space (up to global) and in time (up to 30 days) using a stochastic forecast capability

Stochastic  
parameterization

*Sources of uncertainty*

Localization of  
Ensemble Trans.

Run ensembles

Post calibration/  
Bias correction

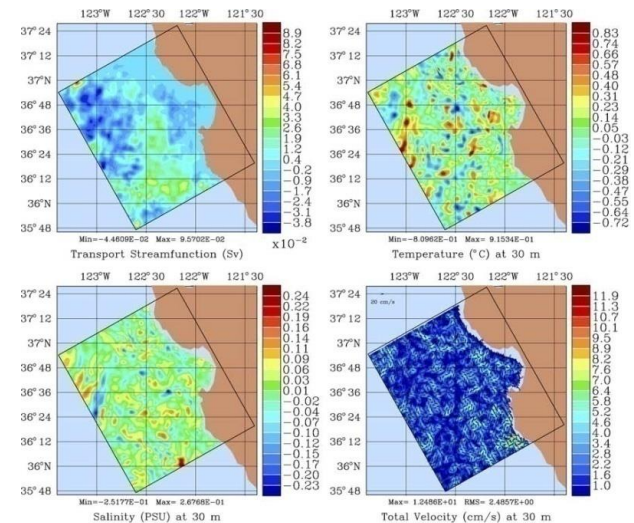
Generate PDFs

Maximum  
Likelihood Estimates

The challenge is to account for neglected or ill-represented processes in the deterministic models associated with subgrid scale processes.

This can lead to insufficient ensemble spread needed to capture the true forecast or even to encompass climatology for longer-range forecasts, as well as insufficient forecast error variance over the length of the forecast.

Here the model errors are modeled using unbiased random noise with a n exponential decorrelation in time



Differences between a deterministic and Stochastic 1-day forecast started from same Initial condition (Lermusiaux, 2006).

***New extended  
range forecast***

Testing and Demo

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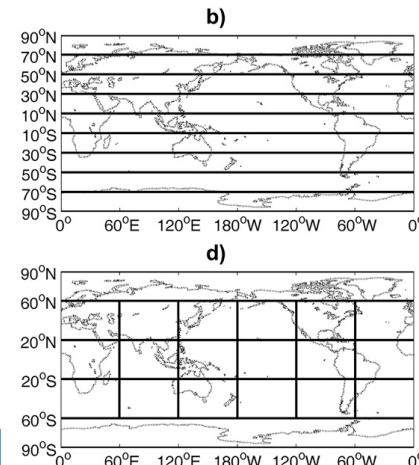
Generate PDFs

Maximum  
Likelihood Estimates

***New extended  
range forecast***

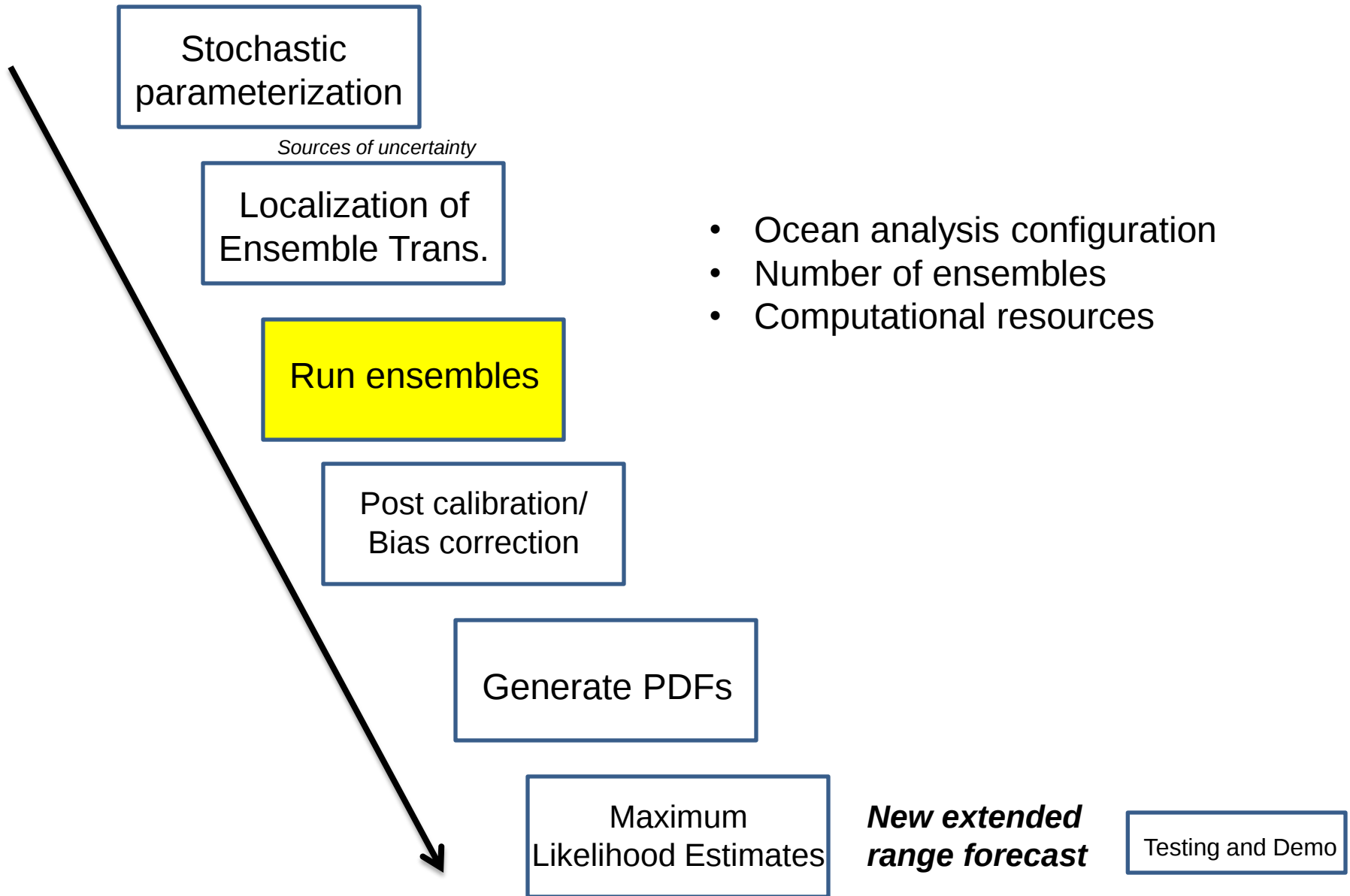
Testing and Demo

- The challenge is to localize the ET to scale and account for local error statistics
- This will not scale to global applications because the number of ensemble members is  $\ll$  than the degrees of freedom (model dimensions) of the model state.
- Solution: localized ET solutions on multiple subdomains or along dynamically adaptive subdomains:



Banded and block  
application of the  
ET to NOGAPS  
(McClay et al., 2009)

**Objective: Extend the Range of Ocean Forecasts in Space (up to global)  
and in time (up to 30 days) using a stochastic forecast capability**



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Challenge: To account for global vs. local biases in key variables and optimize spread skill over regions and variables of interest.

This can be done via Bayesian Analysis using the local NCODA analysis, other sources of information (regional runs if available), and climatology as constraints to compute the likelihood functions from the prior ensemble population.

$$\text{Posterior} = \frac{\text{Likelihood Function}}{p(y^a)} \times \text{Prior}$$
$$p(x \setminus y^a) = \frac{p(y^a \setminus x)}{p(y^a)} \times p(x)$$

$x$  = ocean state

$p(x)$  = global ensemble distribution

$y^a$  = constraints from other sources

***New extended  
range forecast***

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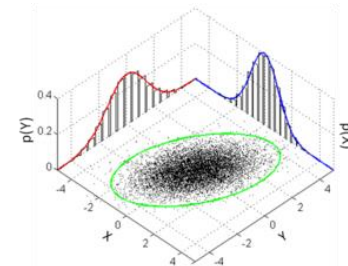
Maximum  
Likelihood Estimates

Challenge: To extract the best forecast and identify the key variables That are influencing the forecast.

This is done by generating joint PDFs from ensemble populations that have a large number of degrees of freedom relative to the ensemble size.

Joint PDFs are constructed statistically, i.e.

- Parametric estimation (e.g. using mean and error covariances)
- Kernel Density Estimation
- Gaussian Mixture Models



***New extended  
range forecast***

Testing and Demo

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Stochastic parameterization

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Post calibration/  
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Maximum  
Likelihood Estimates

***New extended  
range forecast***

Testing and Demo

Challenge: To extract the best forecast and identify the key variables that are influencing the forecast.

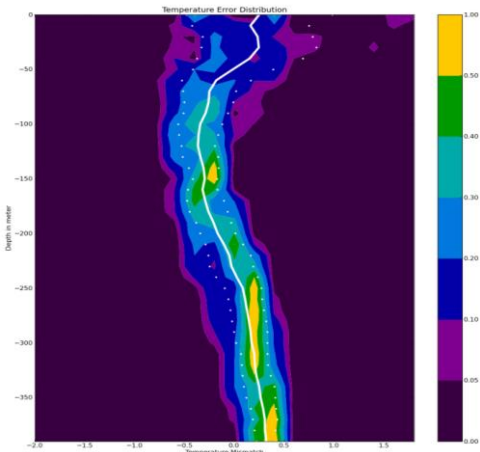
Done by identifying local and global maxima in the Joint PDFs.

The JPDFS are complex functions (high dimensionality), thus they require the exploitation of robust algorithms to search out these inflection points

Complex algorithms to be explored include:

- gradient analyses of PDFs
- steepest decent
- genetic algorithms

The maximum likelihood estimate and probability of joint occurrence will be used to extract the maximum likelihood, which will give a more accurate forecast than the any of the ensemble members, the ensemble mean, or the deterministic (control run) mean.



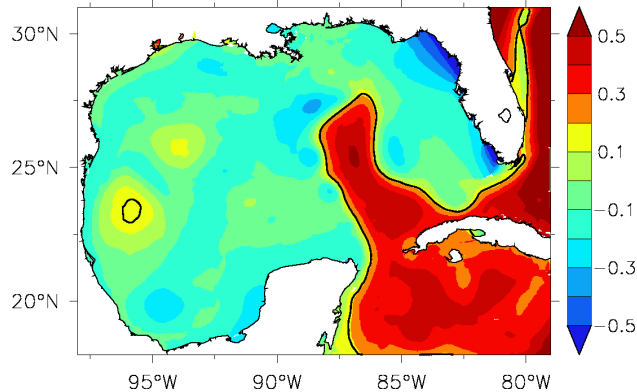
Color = likelihood (0-1)  
White = observed mean error



# 8-Week Ensemble Forecast

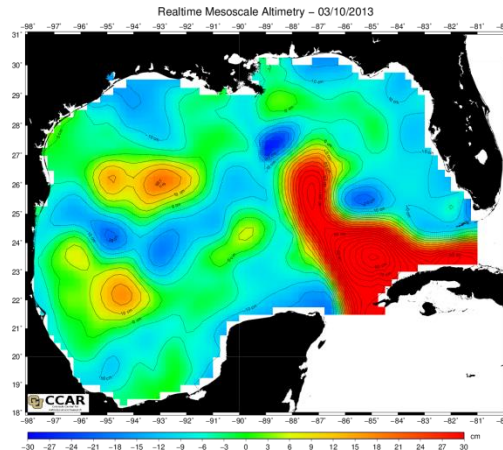
## Analysis: March 10

SSH (m), A=20130310, F=20130310, 32-Members  
0.17m at 000-m (contour), Ens Mean, Mean (shaded)



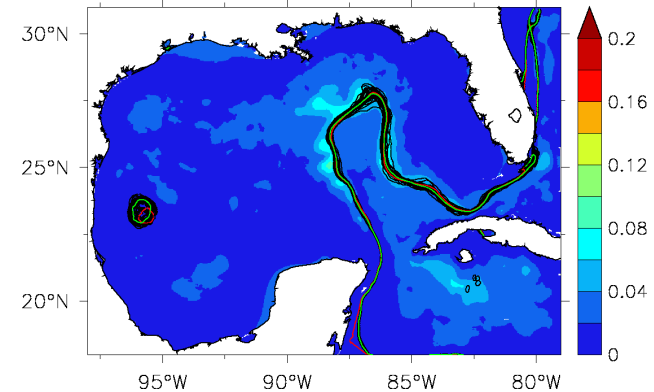
## Mean (17 cm) SSH

## Altimetry: March 10



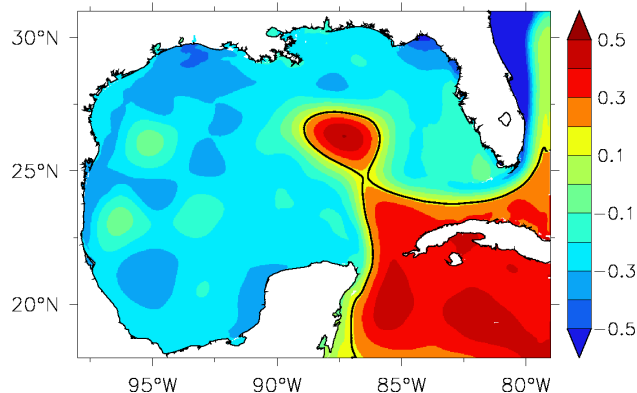
## Analysis: March 10

SSH (m), A=20130310, F=20130310, 32-Members  
0.17m at 000-m (contour), Control, Ens Mean, Std. Dev. (shaded)

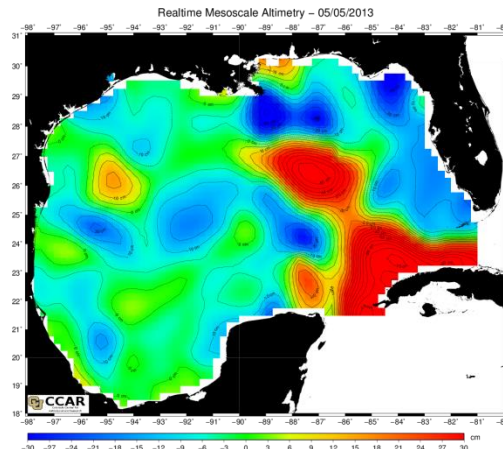


## Std. Dev. (17 cm) SSH

SSH (m), A=20130310, F=20130505, 32-Members  
0.17m at 000-m (contour), Ens Mean, Mean (shaded)

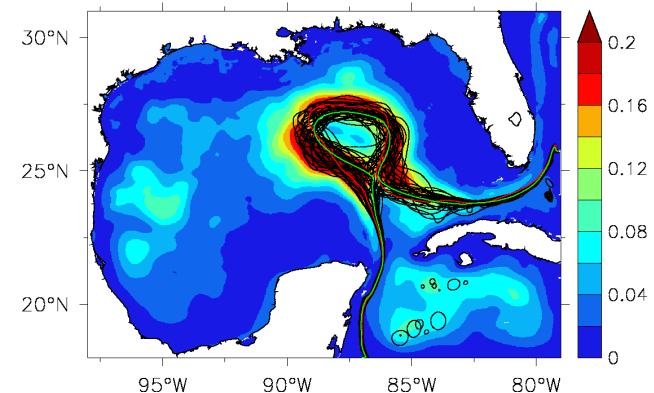


## Forecast: May 05



## Altimetry: May 05

SSH (m), A=20130310, F=20130505, 32-Members  
0.17m at 000-m (contour), Control, Ens Mean, Std. Dev. (shaded)



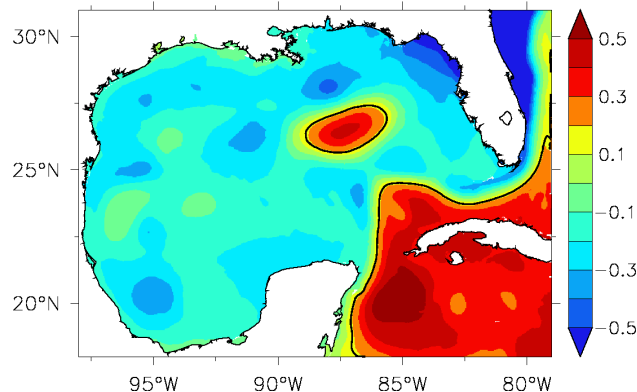
## Forecast: May 05



# 8-Week Ensemble Forecast

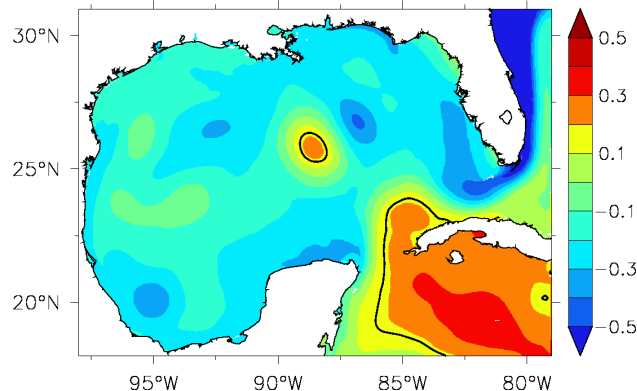
## Analysis: April 21

SSH (m), A=20130421, F=20130421, 32-Members  
0.17m at 000-m (contour), Ens Mean, Mean (shaded)



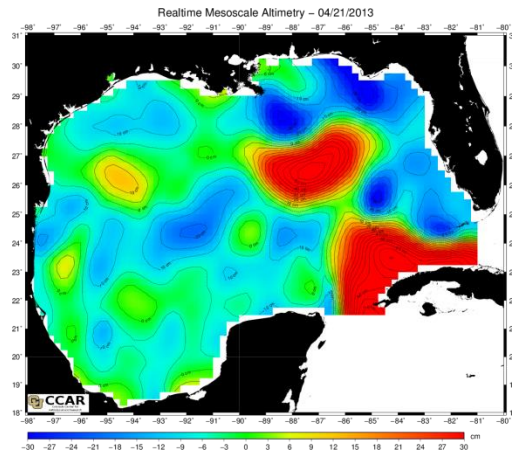
## Mean (17 cm) SSH

SSH (m), A=20130421, F=20130616, 32-Members  
0.17m at 000-m (contour), Ens Mean, Mean (shaded)

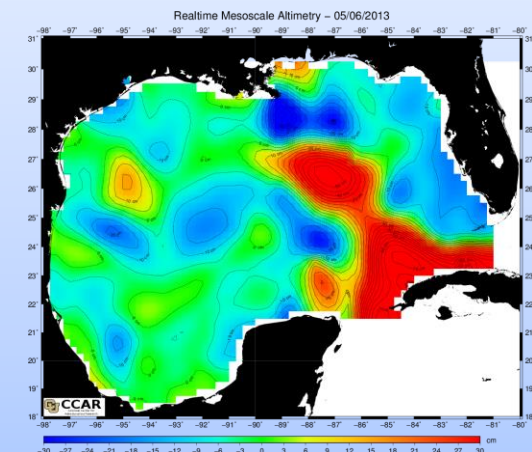


## Forecast: June 16

## Altimetry: April 21



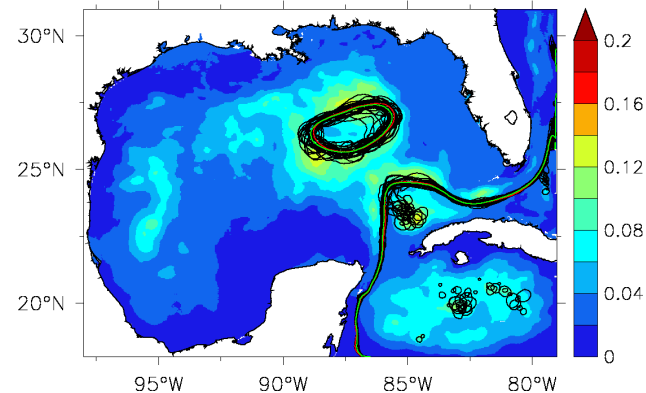
## Altimetry: May 6



## Altimetry: June 16???

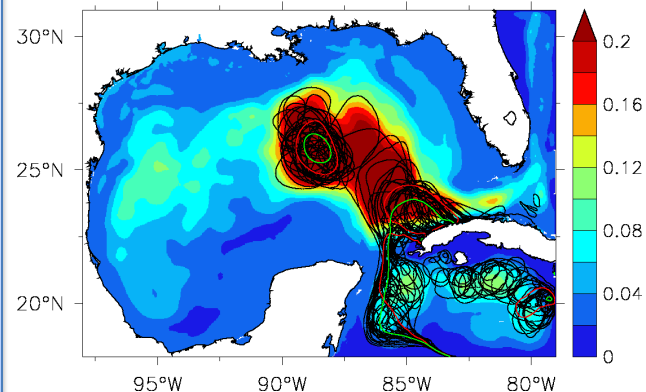
## Analysis: April 21

SSH (m), A=20130421, F=20130421, 32-Members  
0.17m at 000-m (contour), Control, Ens Mean, Std. Dev. (shaded)



## Std. Dev. (17 cm) SSH

SSH (m), A=20130421, F=20130616, 32-Members  
0.17m at 000-m (contour), Control, Ens Mean, Std. Dev. (shaded)



## Forecast: June 16

# Thanks!

***SUPPLEMENTAL SLIDES  
FOLLOW***